Rate Adaptation for Terahertz Communications

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***Abstract*—The large available bandwidth of terahertz (THz) channels makes THz technology a promising approach to achieve very high data rates for future applications. In this paper, we characterize the THz channel using detailed measurement and analysis. Based on the results, we choose three THz bands in which atmospheric attenuation is smaller compared to other bands. We propose two rate adaptive downlink THz algorithms in which the modulation order is changed based on the channel properties of individual receivers. We demonstrate data rates of several Gbps per user while maintaining fairness.**

***Index Terms*—Adaptive THz algorithm, channel characterization, continuous wave.**

I. Introduction

We have all experienced the frustration of very slow downloads of content (say a movie or a book) while waiting at the airport. The reason is that while there has been significant improvement in wireless speeds with the emergence of innovative technologies, the demand for this resource invariably exceeds capacity. Recently, researchers have begun developing transceiver technology for use at terahertz frequency bands. Since this band extends from 100 GHz to 10 THz, it has enormous available bandwidth and can potentially overcome bandwidth limitations we see at wifi frequencies.

Assume the presence of a terahertz access point (TAP) located in the ceiling so that it has line of sight (LOS) to all the potential users. Let us also assume that there is a wifi link between the users and the TAP. The wifi link is used as the control channel for the terahertz downlink. The wifi link is used in the normal way to register users into the network and to access the Internet but when sending large amounts of data to the user, the TAP sends the data stream over the terahertz channel.

While the terahertz channel has the benefit of large available bandwidth, it is well absorbed by water in the atmosphere (as well as some other molecules). Further, terahertz signals are dramatically attenuated on reflection and thus terahertz applications may well be limited to indoor and LOS scenarios [1]. In this paper we develop two downlink rate adaptation algorithms that use knowledge of the channel at each receiver (via the wifi channel) to *maximize throughput* to each user and *maintain fairness*. Our specific contributions are:

- We perform measurements of the terahertz channel using *omni-directional antennas*. These measurements are used to construct accurate channel models as a function of distance, humidity, and atmospheric pressure.
- Using the omni-directonal channel models for three frequency bands (237.5 GHz, 667.5 GHz, and 872.5 GHz) that have lower attenuation, we build detailed simulation models for a TAP. This simulator is then used for evaluating two different rate adaptation algorithms.
- We present simulation results where we illustrate the very high data rates achieved as well as examine fairness in channel allocation. When using a single 35 GHz channel centered at 237.5 GHz, we show aggregate data rates of 40 Gbps for ten users at distances of up to 20 m. When we use all three channels, we get an aggregate data rate of 100 Gbps.

The remainder of the paper is organized as follows. The next section presents related work in terahertz communications. Section III presents our terahertz channel model which is then used for the simulations. Section IV describes our rate adaptation algorithms. Section V summarizes our simulation experimental design and presents the simulation results. Finally, we summarize the work in section VI.

II. Related Work

Terahertz communication has gained a great deal of attention as the technology that can achieve Tbps data rates. Since the THz bands are not reserved to any specific application, it is possible to employ this large bandwidth for wireless communication and achieve high data rates [2]–[5].

Rate adaptation algorithms are used extensively in modern communication systems. The purpose of these algorithms is to enable the transmitter to adapt the modulation and transmit power in order to optimize the channel utilization. In cellular systems, as a user moves, the receiver channel varies very rapidly. Therefore, all cellular standards include a feedback channel from the receiver to the transmitter which informs the transmitter about the current receiver channel conditions. Unlike cellular systems, 802.11 a/b/g do not contain a feedback channel. In this paper, we use a wifi channel to serve the purpose of the feedback channel from the receiver to the transmitter and adapt the modulation at the transmitter to maximize throughput.

III. Channel Model

As we mentioned earlier, one of the primary impairments of the THz channel is that as the signal propagates through the air, molecules in the air, specially water vapor, absorb the

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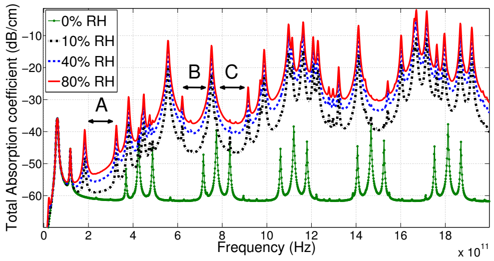

Fig. 1. Atmospheric attenuation coefficient for multiple relative humidity (RH) levels.

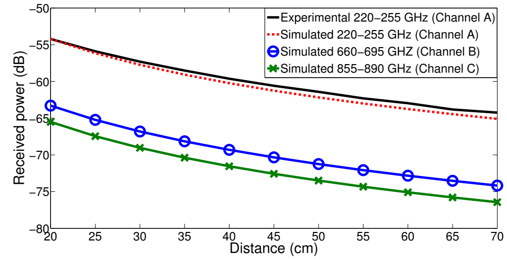

Fig. 2. Received power of 220–255 GHz (channel A), 660–695 GHz (channel B), and 855–890 GHz (channel C) using omni-directional antennas.

signal's energy. As a result, the relative humidity (RH) of the air and the Tx-Rx distance affect the received signal's quality. Since this absorption is a function of frequency, selecting the carrier frequency at which the THz signal is not attenuated drastically is important.

Using Van Vleck-Weisskopt (VVW) line shape and HITRAN molecular absorption database [6], we calculate the molecule absorption lines up to 2 THz for water vapor, oxygen, nitrogen, and carbon dioxide. Fig. 1 shows the calculated atmospheric attenuation coefficient in dB/cm as a function of frequency for the range of 0–2 THz. The result shows that with a higher humidity, we will have a higher absorption coefficient. Also, there are three windows A, B, and C in which the absorption coefficient is smaller comparing to the other frequency bands. Hence, we use the center carrier frequencies of 237.5 GHz (channel A), 677.5 GHz (channel B) and 872.5 GHz (channel C) with the bandwidth of 35 GHz in this paper.

According to Beer-Lambart law, the transmission of the signal is exponentially decreased with Tx-Rx distance. Also, Based on Friis equation, in the case of omni-directional antennas, we should consider the effect of free space path loss on the received signal. Therefore, the transfer function for our channel is as follows.

$$\boxed{H(f) = \frac{\lambda}{4\pi d} \times e^{-(i2\pi f\tau + dK(f))}} \tag{1}$$

Here, i is the imaginary unit, λ is the wavelength in cm, d is the Tx-Rx distance in cm, τ is the propagation time in seconds through distance d, and $K(f)$ is the attenuation coefficient for frequency f from Fig. 1.

We measured the impulse response of the channel experimentally using Picometrix 4000 system in our lab for distances 20–70 cm. Fig. 2 shows the received signal's power using different channels when RH is 40%. The solid line is the result that we got from our lab experiment corresponding to channel A and dotted line is the corresponding result that we calculated based on the transfer function from (1). The figure shows that the experimental result is in close agreement with the result from our proposed channel model. Also, by comparing the result for channels A, B, and C we see that the signal corresponding to a channel with a higher center frequency is attenuated more. The reason is that with a higher frequency the wavelength is smaller; therefore, from (1) the received signal has a lower intensity.

IV. Rate Adaptation Algorithms

We develop two rate adaptation algorithms in which TAP adapts the modulation order based on the channel parameters. In the first algorithm we use a single channel only and we call it single channel algorithm (SCA). Later, in section IV-B, we develop a second algorithm that utilizes all three channels together to increase the data rate and we call it multiple channel algorithm (MCA). We assume that the wifi channel is used to estimate the distance to each user and the TAP measures the relative humidity of the air. Using this information, the TAP can compute the expected $\mathrm{E_b/N_0}$ (energy per bit to the spectral noise density) for different users and different modulation schemes. Then it selects the highest order modulation with BER $\leq$ BER$_T$, where BER$_T$ is the maximum BER (bit error rate) that can be tolerated at each receiver. We use MPSK (phase shift keying) modulation in which M is changed based on the user distance from the TAP.

A. Single Channel Algorithm (SCA)

To have a fair connection in which all users can achieve similar data rates, TAP sends data to each user in a time devision multiplexing (TDM) system. For that, TAP assigns the smallest time slot, T_{min}, to the user that has the highest order modulation. For users with lower order modulations, TAP selects multiples of T_{min} such that all users receive almost the same data rate.

In general, the ith user in its time slot receives the upper bound of b_i bits of error free information.

$$b_i = \left\lfloor \frac{T_i}{T_s} \right\rfloor \log_2 M_i - [\text{BER} \times \left\lfloor \frac{T_i}{T_s} \right\rfloor \log_2 M_i] \tag{2}$$

Here, T_s is the symbol time, T_i is the time slot, M_i is the modulation order that are assigned to the ith user.

B. Multiple Channel Algorithm (MCA)

In this algorithm, TAP uses channels A, B, and C simultaneously to send data to users and achieve higher data rate for each user. As we will see later in section V, each channel covers different ranges of TAP-user distances.

In MCA, time slots with the same duration T are assigned to all users. In each time slot, TAP sends data to three users using different channels such that fairness is maintained among users and the highest data rate is achieved. The following is the rate adaptation algorithm that is used in MCA.

Multiple Channel Algorithm (MCA)

Assign $C = 0$ to all users
R_A: The longest distance coverable by channel A
R_B: The longest distance coverable by channel B
R_C: The longest distance coverable by channel C
for each $timeSlot$ **do**
  $minC_A$=Min(C) of users with distances$\leq R_A$
  Find the user with the longest distance that has $C = minC_A$, assign channel A to it
  If a user is found, find the highest order modulation method using channel A that has BER$\leq$BER$_T$ and
  Add the $log_2 M$ corresponding to the selected modulation to the user's C
  $minC_B$=Min(C) of users with distances$\leq R_B$
  Find the user with the shortest distance that is in $(R_C, R_B]$ and has $C = minC_B$, assign channel B to it
  If did not find such user, find the user with the longest distance$\leq R_C$ that has $C = minC_B$, assign channel B to it
  If a user is found, find the highest order modulation method using channel B that has BER$\leq$BER$_T$ and
  Add the $log_2 M$ corresponding to the selected modulation to the user's C
  $minC_C$=Min(C) of users with distances$\leq R_C$
  Find the user with the shortest distance that has $C = minC_C$, assign channel C to it
  If a user is found, find the highest order modulation method using channel C with BER$\leq$BER$_T$ and
  Add the $\log_2 M$ corresponding to the selected modulation to the user's C
end for

MCA keeps track of the downlink data rate that is assigned to each user with the C variable. The upper bound of the received data bits for the ith user is equal to the following.

$$b_i = \sum_{t=1}^{K} \sum_{z=1}^{3} \left(\left\lfloor \frac{T}{T_s} \right\rfloor \log_2 M_{iz} - [\mathrm{BER}_{iz} \times \left\lfloor \frac{T}{T_s} \right\rfloor \log_2 M_{iz}] \right) \tag{3}$$

Here, T is the duration of each time slot, K is the number of time slots, M_{iz} is the modulation order and BER$_{iz}$ is the bit error rate for the ith user that is receiving data on channel z, where $z = 1$, $z = 2$, and $z = 3$ correspond to channels A, B, and C, respectively.

V. Simulation Results

We choose BPSK, QPSK, 8PSK, and 16PSK modulation in our rate adaptive algorithms and use Matlab for simulation. The symbol rate of our system is set to 25 GBd/s and we use the raised cosine filter with rolloff factor 0.4. Fig. 3 shows

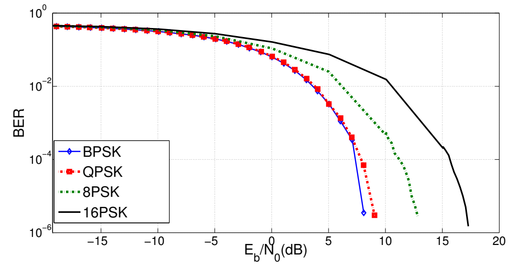

Fig. 3. Bit error rate (BER) vs received E_b/N_0 for modulation methods.

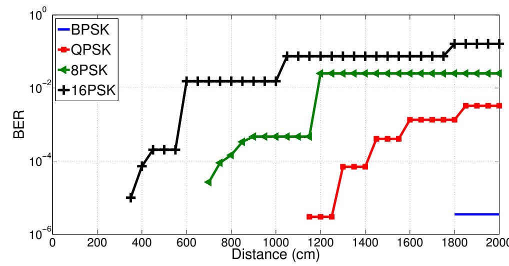

Fig. 4. BER vs distance (cm) for modulation methods using channel A.

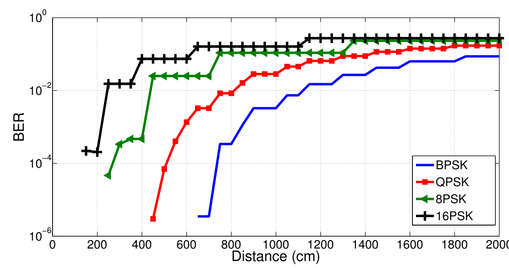

Fig. 5. BER vs distance (cm) for modulation methods using channel B.

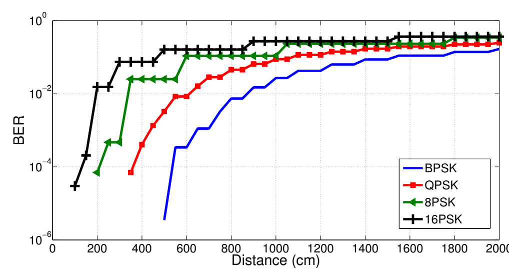

Fig. 6. BER vs distance (cm) for modulation methods using channel C.

BER corresponding to all modulation methods for received E_b/N_0 (dB). We set the BER$_T$ to 10^{-4}.

Based on the channel model from (1) and the transmitter power of 35 mW, we calculate the received E_b/N_0 and the corresponding BER for TAP-user distances of 100–2000 cm for channels A, B, and C. Figures 4–6 show BER vs distance for the modulation methods when we use channel A, B, or C, respectively. We should note that BER less than 10^{-6} is not shown in the figures.

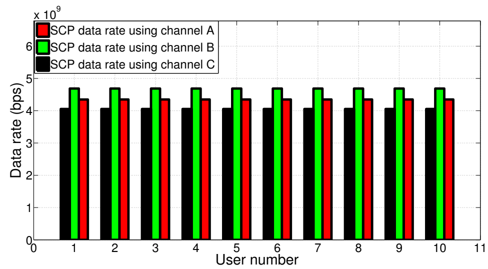

Fig. 7. SCA downlink data rate when TAP uses channel A, B, or C.

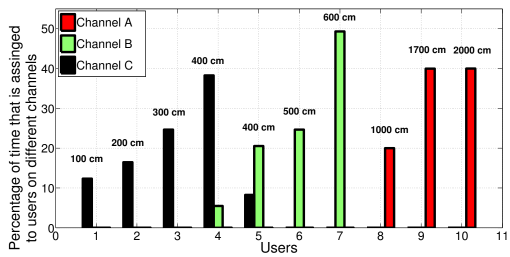

Fig. 8. The percentage of time that TAP assigns different channels to each user in MCA.

A. SCA Simulation Results

For simulation, we assume there are 10 users at different distances. Based on the result from Fig. 4, when TAP uses channel A, it can send data to users with distances up to 2000 cm with BER<BER_T. Similarly, from the result of Fig. 5, when TAP uses channel B, it covers users with distances up to 700 cm. Finally, the result from Fig. 6 shows that TAP can cover users with distances up to 500 cm using channel C.

To maintain fairness between the users TAP assigns a time slot to each user such that all users achieve the same data rate. We set T_{min} to be 600μs.

We assign TAP-user distances of up to 2000cm, 700cm, and 500 cm when TAP uses channel A, B, or C, respectively.

Fig. 7 shows the data rate that each user achieves when TAP uses channel A, B, or C. As is obvious, in all cases the fairness is maintained and all of the users achieve the same data rate.

B. MCA Simulation Results

In this section we show the simulation result when using MCA. Again, we assume that we have 10 users and randomly assign TAP-user distances up to 2000 cm to them. We consider the time slot duration, T, of 200μs. We use the MCA and run the program for 5000 time slots.

Fig. 8 shows the percentage of time that TAP assigns to users on each channel and Fig. 9 shows the achieved data rate for each user. As we see, users 8–10 achieve lower data rate in comparison to other users. That is, because of the long TAP-user distances, only channel A can cover these users with a low modulation order. Hence, TAP uses channel A only for these three users and their achieved data rate could not go any higher. At the same time TAP uses channel B to send data to users 4–7 and channel C for users 1–5.

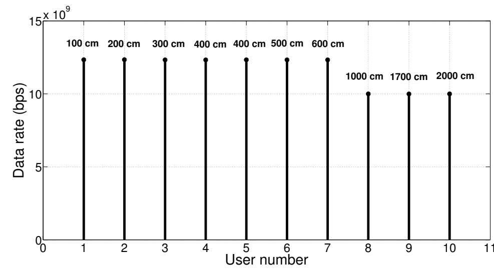

Fig. 9. MCA downlink data rate.

VI. Conclusions

In this paper, based on analysis and our detailed channel measurements we characterized THz channel utilizing omni-directional antennas. We proposed THz rate adaptation algorithms that use single or multiple channels for sending downlink data to users with different distances. We also provided the simulations utilizing our proposed algorithms. The results showed that fairness is maintained in our channel and the users receive high data rates. For the single channel case, each user receives 4 Gbps data rate while for the multiple channel case, data rates of 10 Gbps/user are achieved.

Acknowledgment

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References

[1] J. Federici and L. Moeller, "Review of terahertz and subterahertz wireless communications," *Journal of Applied Physics*, vol. 107, no. 11, 2010.

[2] H. Song, K. Ajito, A. Hirata, A. Wakatsuki, T. Furuta, N. Kukutsu, and T. Nagatsuma, "Multi-gigabit wireless data transmission at over 200-GHz," in *34th International Conference on Infrared, Millimeter, and Terahertz Waves, 2009. IRMMW-THz 2009*, 2009, pp. 1–2.

[3] I. Kallfass, J. Antes, T. Schneider, F. Kurz, D. Lopez-Diaz, S. Diebold, H. Massler, A. Leuther, and A. Tessmann, "All active MMIC-based wireless communication at 220 GHz," *IEEE Transactions on Terahertz Science and Technology*, vol. 1, no. 2, pp. 477–487, November 2011.

[4] B. Zhang, Y.-Z. Xiong, L. Wang, and S. Hu, "A switch-based ASK modulator for 10 Gbps 135 GHz communication by 0.13 MOSFET," *IEEE Microwave and Wireless Components Letters*, vol. 22, no. 8, pp. 415–417, 2012.

[5] S. Koenig, D. Lopez-Diaz, J. Antes, F. Boes, R. Henneberger, A. Leuther, A. Tessmann, R. Schmogrow, D. Hillerkuss, R. Palmer, T. Zwick, C. Koos, W. Freude, O. Ambacher, J. Leuthold, and I. Kallfass, "Wireless sub-THz communication system with high data rate," *Nature Photonics*, vol. 7, pp. 977–981, October 2013.

[6] L. Rothman, I. Gordon, Y. Babikov, A. Barbe, D. C. Benner, P. Bernath, M. Birk, L. Bizzocchi, V. Boudon, L. Brown *et al.*, "The hitran2012 molecular spectroscopic database," *Journal of Quantitative Spectroscopy and Radiative Transfer*, vol. 130, pp. 4–50, 2013.